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BRITTLE TORSIONAL FATIGUE CRACK INITIATION IN AN OTHERWISE DUCTILE ENVIRONMENT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of a torsional fatigue test program on marage 250 steel indicate that the usual fatigue failure mechanism occurs as a flat ductile fracture along the cross section of the test specimens. However, a small number of specimens displayed a small penny-shaped crack on the outer surface at a 45-degree helix, typical of brittle torsional failure, before the final ductile failure. Scanning electron microscope examination showed that the brittle failure was caused by a brittle inclusion on the outside surface of the specimen.

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The authors gratefully acknowledge the assistance of Ronald T. Abbott of the Materials Engineering Branch for testing the specimens in the torsional fatigue testing program; Mark Fleszar and co-workers of the Advanced Technology Branch for the chemical analysis; and from the Physical Sciences Branch, Charles Nolan for supervision of the mechanical testing program and Christopher Rickard for the metallography work.

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INTRODUCTION

A torsional fatigue test program was designed to generate torsional fatigue data over a wide range of twist moments and fatigue life, using two different steels for comparison: AISI 4150H and marage 250 steel. A comparison of these results will be presented in another report. In this report we discuss a phenomenon that occurred with a small number of specimens of marage 250 during testing. Approximately 60 specimens were tested to failure in torsional fatigue, and most of them failed in the characteristic manner of ductile torsional failure--a flat fracture parallel to the twisting plane and normal to the specimen longitudinal axis. However, a few specimens indicated brittle fatigue crack initiation.

ANALYSIS

A chemical analysis of marage 250 steel apppears in Table I. All the elements appear to be within the normal range. The titanium content is in the

TABLE I. CHEMICAL ANALYSIS OF MARAGE 250 STEEL

Element	Range	Actual
Carbon	0.03 Max	0.007
Manganese	0.10 Max	0.01
Nickel	17.0 - 19.0	18.28
Phosphorus	0.01 Max	0.005
Sulphur	0.01 Max	0.003
Silicon	0.10 Max	0.02
Molybdenum	4.6 - 5.1	4.83
Titanium	0.30 - 0.50	0.50
Aluminum	0.05 - 0.15	0.12
Cobalt	7.0 - 8.5	7.77

upper level of the normal range, 0.50 percent actual level of the 0.30 to 0.50 percent expected range. The importance of this value is discussed later in this report.

The mechanical properties of marage 250 steel are presented in Table II. All the test specimens were manufactured in the longitudinal direction from 1 1/2-inch round bar stock. The tests performed were tensile, Charpy V-notch energy, hardness, and slow-bend fracture toughness.

TABLE II. MECHANICAL PROPERTIES OF MARAGE 250

	Property	1	2	3	4	Av. Value
Marage 250	0.2% YS, Ksi	255	264	259	258	259.0
Steel	UTS, Ksi	274	278	274	275	275.3
Tensile	% Elongation	10	9	10	9	9.5
Data	% Red Area	55	53	54	54	54.0
	Charpy V					
	Test Temp, °F	-40	-40	-40		-40
	Ft-lbs	16	15	15		15.3
	Slow Bend					
	Test Temp, °F	-40	-40	-40		-40
	K_{Ic} - Ksi$\sqrt{\text{in.}}$	89.7	82.0	93.4		
		91.0	82.3	95.8		89.0

Heat treatment: 1,700°F, 1 hour air-cooled + 1,400°F, 4 hours air-cooled + 900°F, 3 hours air-cooled
Hardness: Rc 52 to 55
All tests: Longitudinal direction from 1 1/2-inch round bar stock
YS: Yield strength
UTS: Ultimate tensile strength

Figure 1a shows a typical ductile torsional fatigue failure. Figure 1b shows the fracture surface of a test specimen at 3x magnification. The pattern in Figure 1b is typical of the ductile radially inward fatigue crack propagation exhibited in ductile torsional fatigue failure. This type of failure occurred in the vast majority of the marage 250 specimens tested.

However, a handful of marage 250 specimens exhibited fatigue crack initiation and propagation on the 45-degree tensile plane, as opposed to the expected transverse shear plane shown by the specimens previously mentioned. One of these different specimens was singled out and examined on the scanning electron microscope (SEM) to account for this difference in fatigue crack mode. The sample chosen was identified as sample #MM-15 which failed at 255,540 cycles.

Figure 2a shows the entire 45-degree crack (area surrounded by ABC) at 10x. Figures 2b, 2c, and 2d show the single initiation site at progressively higher magnifications. Figure 2d at 10,000x shows what appears to be a defect at the initiation site. However. the defect could not be identified.

Examination of the mating fracture surface reveals a large embedded particle at the initiation, shown in Figure 3a at 2,000x. The particle is identified as "P" in Figure 3b at 5,000x. An energy dispersive x-ray (EDX) analysis, shown in Figure 3c, shows the particle to be rich in titanium compared to the adjacent matrix, shown in Figure 3d. Since our x-ray analyzer cannot detect Atomic Number $Z < \#11$ (i.e., sodium), the particle may also contain atomic species below #11, specifically boron, carbon, oxygen, and/or nitrogen, for which titanium has a very strong affinity.

Figure 4 at 4,000x, highly tilted to view the 45-degree fracture surface, shows that the particle lies close to, and may have even intersected, the sample surface. The particle appears to be a single piece of material. Also, since the particle can be positively identified on only one of the two mating fracture surfaces, it appears that the crack had started by particle/matrix decohesion, as opposed to particle cracking.

The 45-degree crack surface was examined along its entire length, and selected areas (5a, 5b, 5c, 5d, 5e, and 5f as noted in Figure 2a) were photographed. Although the crystallographic appearance of the fracture surface is consistent with high cycle fatigue, no fatigue striations could be found at the origin, Figure 5a at 4,000x, or for the first half of the crack. This is probably due to the lack of microscopic resolution and contrast and to the rubbing of the mating fracture surfaces during subsequent cracking.

Conclusive striations were found in the area remote from the origin, Figures 5b through 5f, all at 10,000x. The striations are typical of stage II fatigue, confirming that crack growth in this 45-degree plane is a result of tensile stress, as opposed to shear stress. The striations seen in Figures 5b through 5f yield an accumulation of about 15,000 cycles in this crack length (0.075 in.). However, the striation density versus crack length curve typically has a very high value at the crack origin, falls rapidly, and flattens out at the end of the fatigue crack. Based on the observed density and on previous work, it appears that the order of magnitude estimate of accrued cycles after initiation on this 45-degree crack is 10^5. This is consistent with the fact that specimen #MM-15 failed at 255,540 cycles, as previously mentioned. Initiation probably occurred early in life because of the large titanium-rich inclusion at the specimen surface.

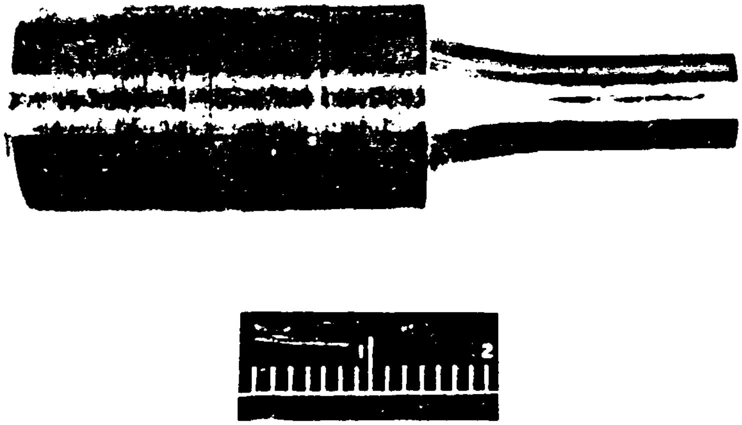
CONCLUSIONS

1. The normal torsional fatigue failure mode for marage 250 steel is the transverse ductile failure as indicated by the vast majority of specimens that failed in this manner.

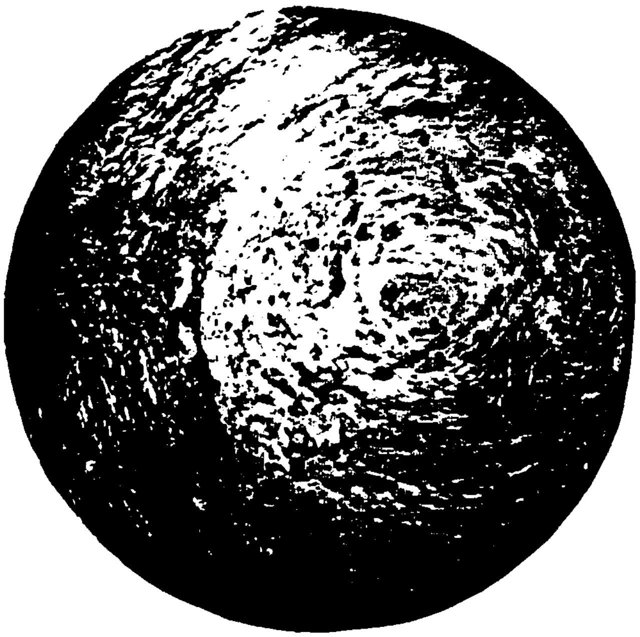
2. The high content of titanium present in the marage 250 steel tested is prone to causing inclusions. However, these inclusions do not affect the normal

ductile failure unless the brittle inclusions are on or near the outside surface of the specimen. Since the torsional stress is maximum on the outside surface, the failure mode would be affected more on the outside of the specimen than on the inside, where the stresses drop off toward the center of the specimen.

3. The fatigue striation analysis indicated that the mode of failure was the result of tensile fatigue in a torsional stress field, as opposed to shear stresses. This means that the specimens with brittle inclusions on the outside surface as crack starters experience brittle fatigue failure.

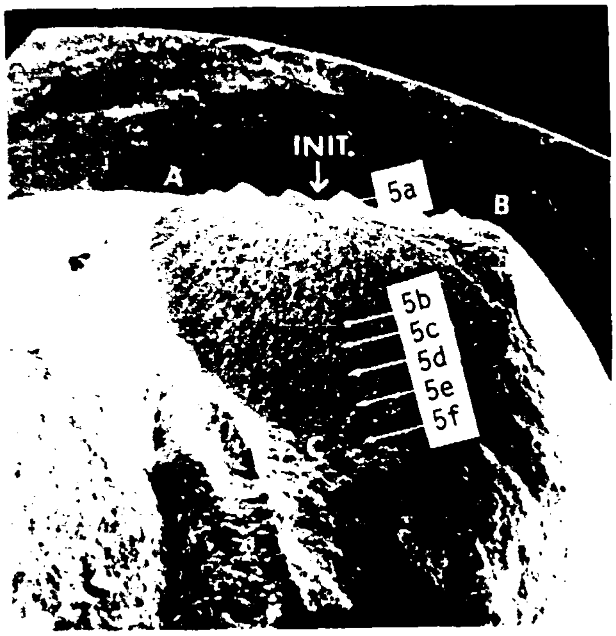


(a) Side view of torsional fatigue test specimen after fracture.



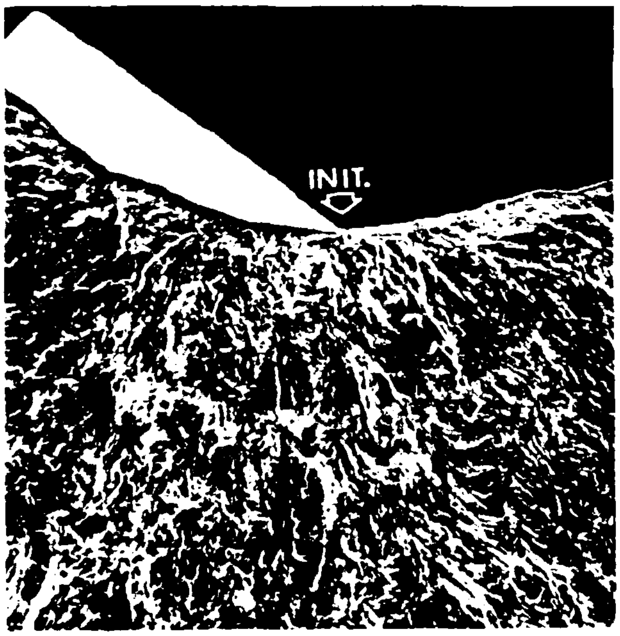
(b) Fracture surface of test specimen, magnification 3x.

Figure 1. Torsional fatigue specimen cycled to failure--marage 250 steel.



(a) Entire 45-degree crack, magnification 10x.

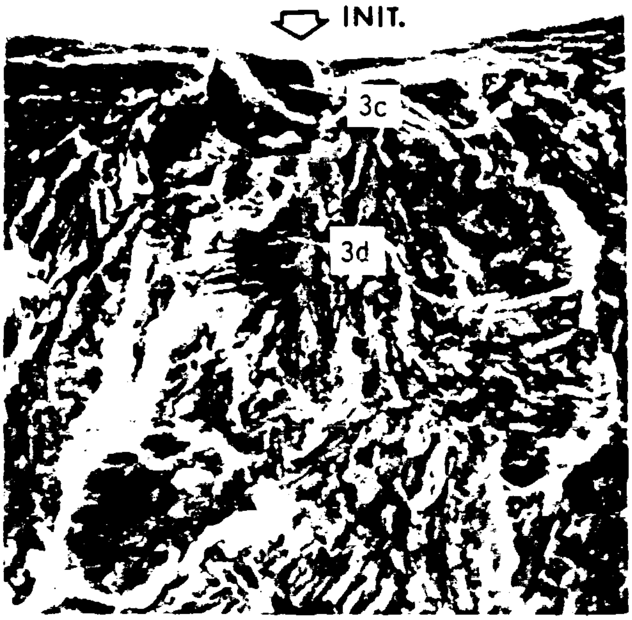
(b) Fatigue crack initiation site, magnification 100x.



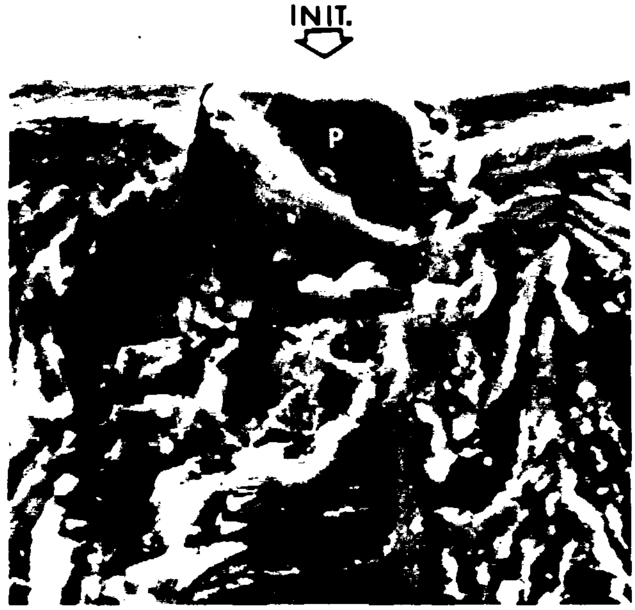
(c) Fatigue crack initiation site, magnification 500x.

(d) Fatigue crack initiation site, magnification 10,000x.

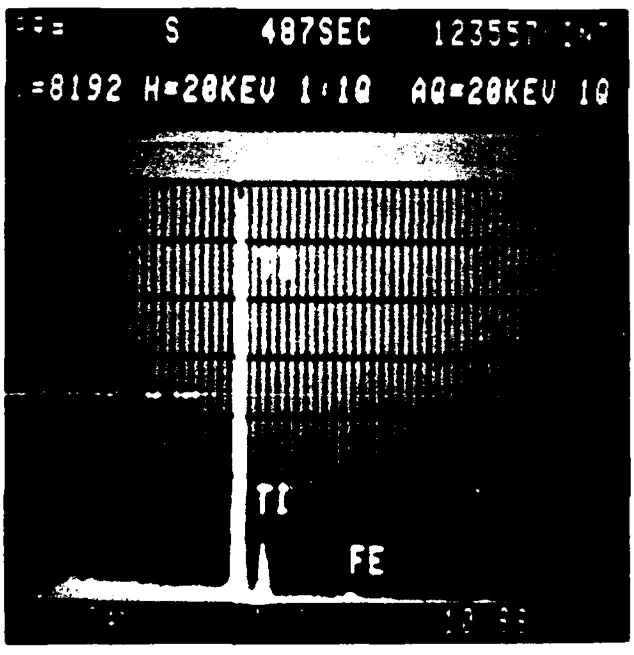
Figure 2



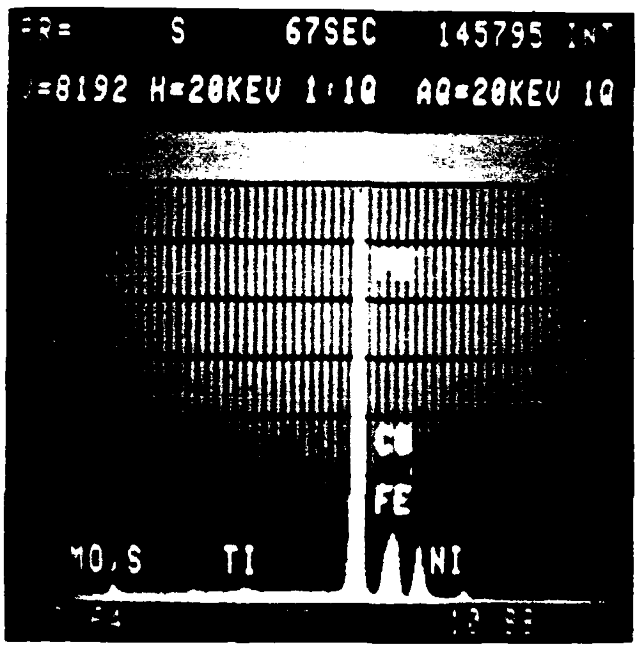
(a) Imbedded particle at initiation site, magnification 2,000x.



(b) Imbedded particle at initiation site, magnification 5,000x.



(c) Energy dispersive x-ray analysis of particle rich in titanium.



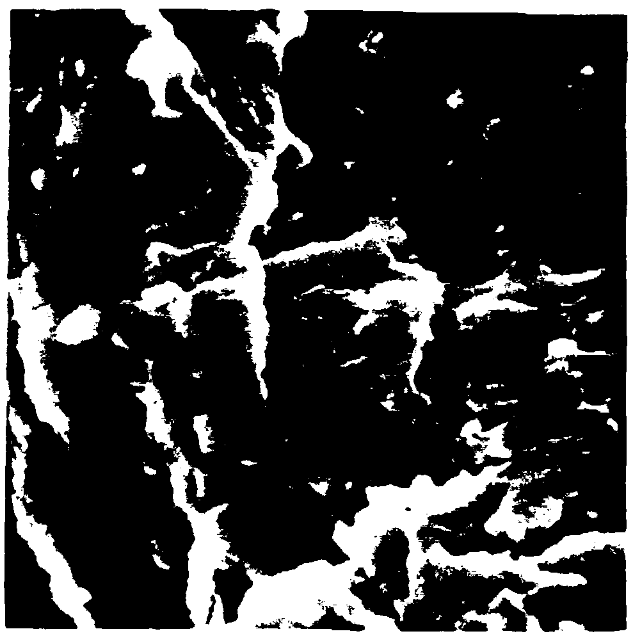
(d) Energy dispersive x-ray analysis of adjacent matrix low in titanium.

Figure 3

Figure 4. Particle at sample surface, magnification 4,000x.

(a) Fracture surface at fatigue crack origin, magnification 4,000x.

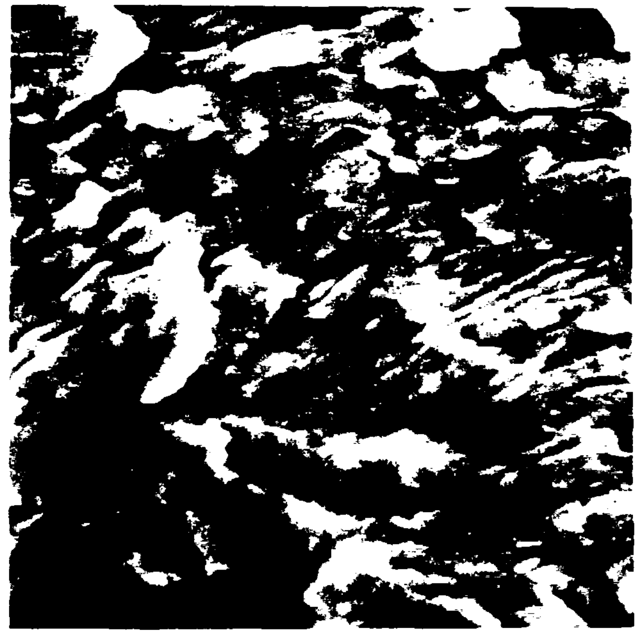
(b) Fracture surface, position b, magnification 10,000x.



(c) Fracture surface, position c, magnification 10,000x.

Figure 5

(d) Fracture surface, position d, magnification 10,000x.



(e) Fracture surface, position e, magnification 10,000x.

(f) Fracture surface, position f, magnification 10,000x.

Figure 5

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